Gas Well De-Liquification Workshop

Adams Mark Hotel, Denver, Colorado

March 5 - 7, 2007

Critical Velocity/ Nodal Stability Gas Well Predictions

By

J F Lea, PLTech LLC

Lynn Rowlan, Echometer Co.

Charlie Reed, Devon

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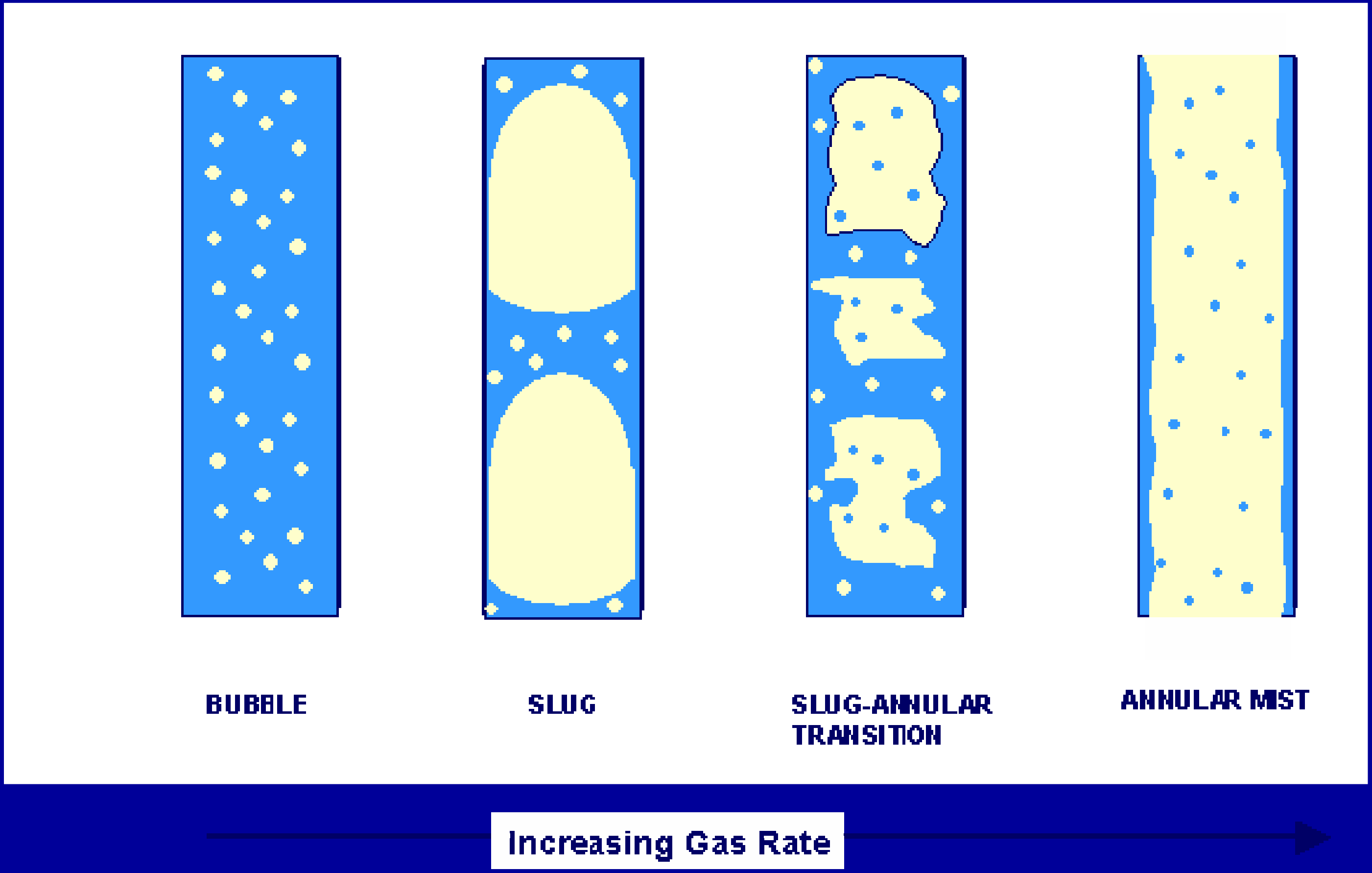
Liquid Loading

GAS WELL GRADIENT COMPOSED OF FRICTION AND GRAVITY

$$(dp/dl) = (dp/dl)el + (dp/dl)f + (dp/dl)acc$$



HOLDUP (LIQUID) BUILDS WITH TIME AND LOWER PRODUCTION

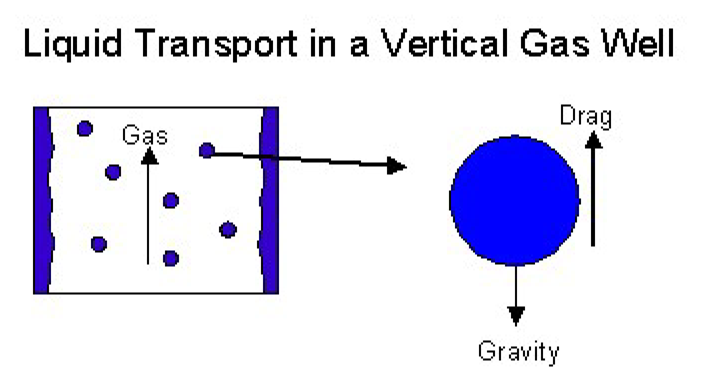
Recognize and Predict Loading by using

“Critical Rate” &

“Nodal Analysis Concepts”

Critical Velocity

Turner Droplet Model


Liquid Transport in a Vertical Gas Well

$$F_{Gravity} = \frac{g}{g_C}(\rho_L - \rho_G) \times \frac{\pi d^3}{6}$$

$$F_{Drag,UP} = \frac{1}{2g_C}\rho_G C_D A_d (V_G - V_d)^2$$

Where

g = gravitational constant = 32.17 ft/s^2
g_C = 32.17 lbm-ft/lbf-s^2
d = droplet diameter
r_L = liquid density
r_G = gas density
C_D = drag coefficient
A_d = droplet projected cross-sectional area
V_G = gas velocity
V_d = droplet velocity

Equate Gravity to Drag Force

$$F_G = F_D$$

$$\frac{g}{g_C}\left(\rho_L - \rho_G\right)\frac{\pi d^3}{6} = \frac{1}{2g_C}\rho_G C_D A_d V_C^2$$

Substituting $A_d = \pi d^2/4$ and solving for V_C gives,

$$V_C = \sqrt{\frac{4g}{3}\frac{\left(\rho_L - \rho_G\right)}{\rho_G}\frac{d}{C_D}}$$

Hinze, AICHE Journal Sept 1955, shows that droplet diameter dependence can be expressed in terms of the dimensionless Weber number

$$N_{WE} = \frac{V_C^2 \rho_G d}{\sigma g_C} = 30$$

Solving for the droplet diameter gives

$$d = 30 \frac{\sigma g_C}{\rho_G V_C^2}$$

and substituting into Equation A-1 gives

$$V_C = \sqrt{\frac{4}{3} \frac{(\rho_L - \rho_G)}{\rho_G} \frac{g}{C_D} 30 \frac{\sigma g_C}{\rho_G V_C^2}}$$

or

$$V_C = \left(\frac{40 g g_C}{C_D} \right)^{1/4} \left(\frac{\rho_L - \rho_G}{\rho_G^2} \sigma \right)^{1/4}$$

Turner assumed a drag coefficient of C_D = .44 that is valid for fully turbulent conditions.
Substituting the turbulent drag coefficient and values for g and g_C gives:

$$V_C = 17.514\left(\frac{\rho_L - \rho_G}{\rho_G^2}\sigma\right)^{1/4} ft/s$$

Where
r_L = liquid density, lbm/ft^3
r_G = gas density, lbm/ft^3
S = surface tension, lbf/ft
Equation A-2 can be written for surface tension in dyne/cm units using the conversion
lbf/ft = .00006852 dyne/cm to give:

$$V_C = 1.593\left(\frac{\rho_L - \rho_G}{\rho_G^2}\sigma\right)^{1/4} ft/s$$

Where
r_L=liquid density, lbm/ft^3
r_G=gas density, lbm/ft^3
s=surface tension, dyne/cm

Evaluate Gas Density Term

Evaluating Equation A-4 for typical values of
Gas gravity γ_G = 0.6
Temperature T = 120 F
Gas deviation factor Z = 0.9
gives:

$$\rho_G = 2.715 \times .6 \frac{P}{(460+120) \times .9} = .0031 P \ lbm / ft^3$$

Typical values for density and surface tension are
Water density = 67 lbm/ft^3
Condensate density = 45 lbm/ft^3
Water surface tension = 60 dyne/cm
Condensate surface tension = 20 dyne/cm

Field Equations

Coleman, et al., (Exxon)

$$V_{C,water} = 1.593\left(\frac{67-.0031P}{(.0031P)^2}60\right)^{1/4} = 4.434\frac{(67-.0031P)^{1/4}}{(.0031P)^{1/2}}\ ft/s$$

$$V_{C,cond} = 1.593\left(\frac{45-.0031P}{(.0031P)^2}20\right)^{1/4} = 3.369\frac{(45-.0031P)^{1/4}}{(.0031P)^{1/2}}\ ft/s$$

Turner et al., (with 20% adjustment)

$$V_{C,water} = 5.321\frac{(67-.0031P)^{1/4}}{(.0031P)^{1/2}}\ ft/s$$

$$V_{C,cond} = 4.043\frac{(45-.0031P)^{1/4}}{(.0031P)^{1/2}}\ ft/s$$

Field Equations: Critical Rate

$$V_{C,water} = 5.321 \frac{(67 - .0031P)^{1/4}}{(.0031P)^{1/2}} \, ft/s$$

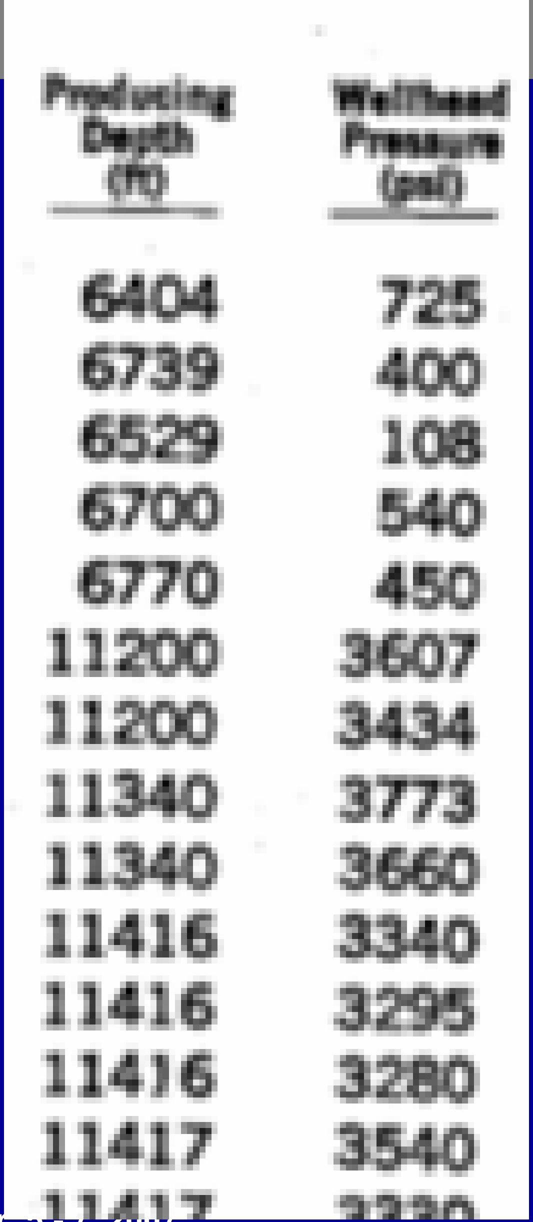
$$V_{C,cond} = 4.043 \frac{(45 - .0031P)^{1/4}}{(.0031P)^{1/2}} \, ft/s$$

$$q_{t,condensate}(MMscf/D) = \frac{.0676 P d_{ti}^{2}}{(T + 460) Z} \frac{(45 - .0031P)^{1/4}}{(.0031P)^{1/2}}$$

$$q_{t,water}(MMscf/D) = \frac{.0890 P d_{ti}^{2}}{(T + 460) Z} \frac{(67 - .0031P)^{1/4}}{(.0031P)^{1/2}}$$

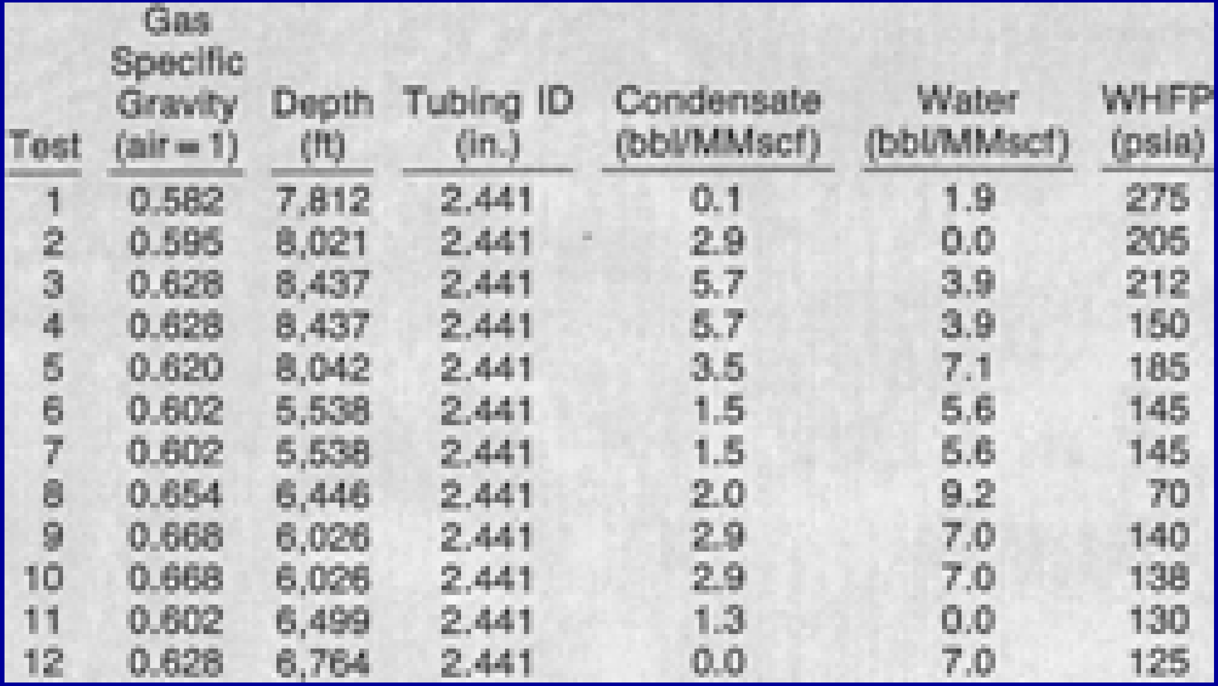
Turner

Well Data



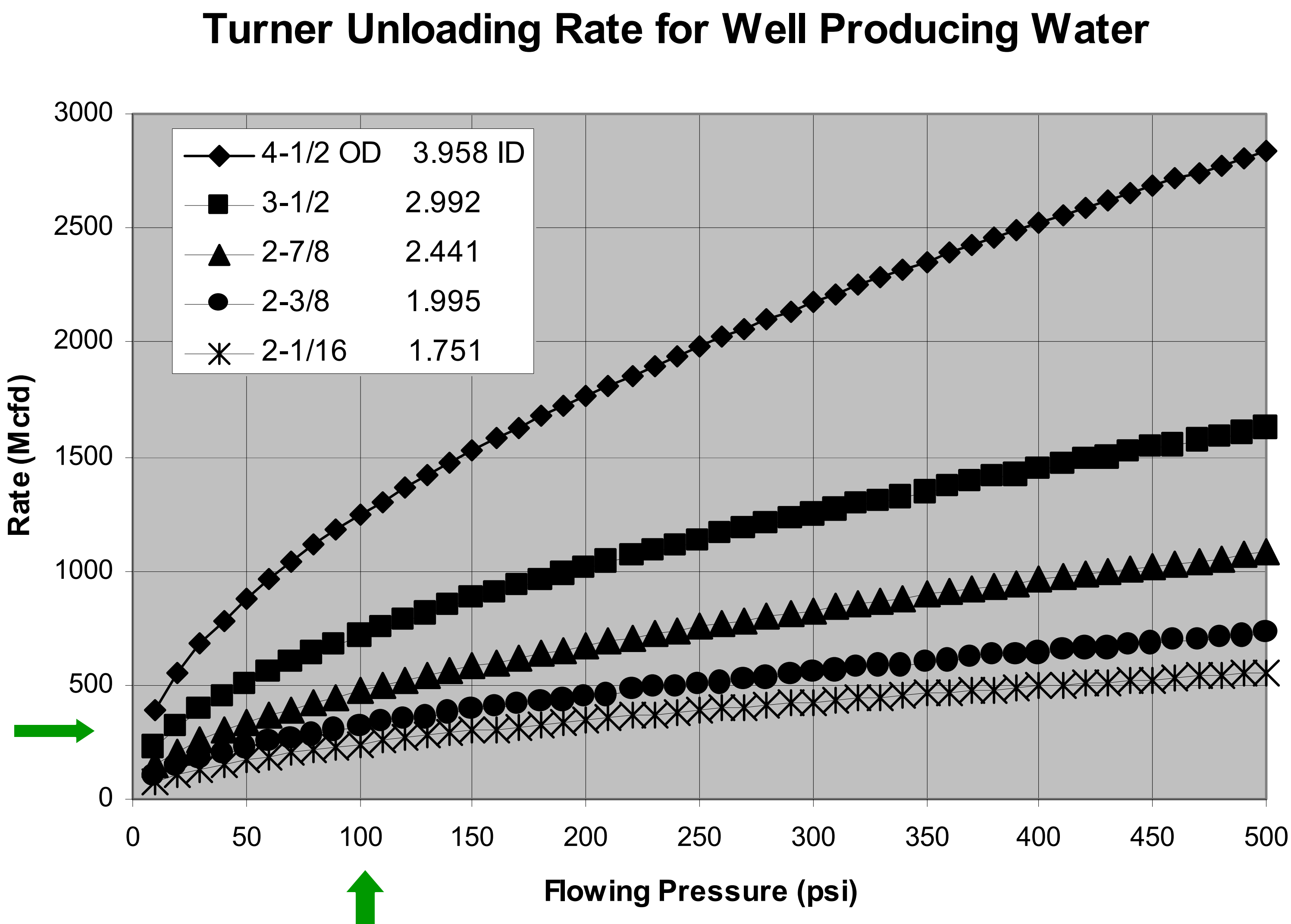
Producing Depth (ft)	Wellhead Pressure (psi)
6404	725
6739	400
6529	108
6700	540
6770	450
11200	3607
11200	3434
11340	3773
11340	3660
11416	3340
11416	3295
11416	3280
11417	3540
11417	[illegible]

Coleman



Test	Gas Specific Gravity (air = 1)	Depth (ft)	Tubing ID (in.)	Condensate (bbl/MMscf)	Water (bbl/MMscf)	WHFP (psia)
1	0.582	7,812	2.441	0.1	1.9	275
2	0.595	8,021	2.441	2.9	0.0	205
3	0.628	8,437	2.441	5.7	3.9	212
4	0.628	8,437	2.441	5.7	3.9	150
5	0.620	8,042	2.441	3.5	7.1	185
6	0.602	5,538	2.441	1.5	5.6	145
7	0.602	5,538	2.441	1.5	5.6	145
8	0.654	6,446	2.441	2.0	9.2	70
9	0.668	6,026	2.441	2.9	7.0	140
10	0.668	6,026	2.441	2.9	7.0	138
11	0.602	6,499	2.441	1.3	0.0	130
12	0.628	6,764	2.441	0.0	7.0	125

Example: Using Turner, 2 3/8's, 100 psi, read~320 Mscf/D



Other References Related to Critical Velocity or Rate

1. Lea, J.F., Nickens, H.V., and Wells, M.: *Gas Well De-Liquification*, first edition, Elsevier Press, Cambridge, MA (2003).
2. Turner, R.G., Hubbard, M.G., and Dukler, A.E.: "Analysis and Prediction of Minimum Flow Rate for the Continuous Removal of Liquids from Gas Wells," *J. Pet. Tech.* (Nov.1969) 1475-1482.
3. Coleman, S.B., Clay, H.B., McCurdy, D.G., and Lee Norris, H. III: "A New Look at Predicting Gas-Well Load Up," *J. Pet. Tech.* (March 1991) 329-333.
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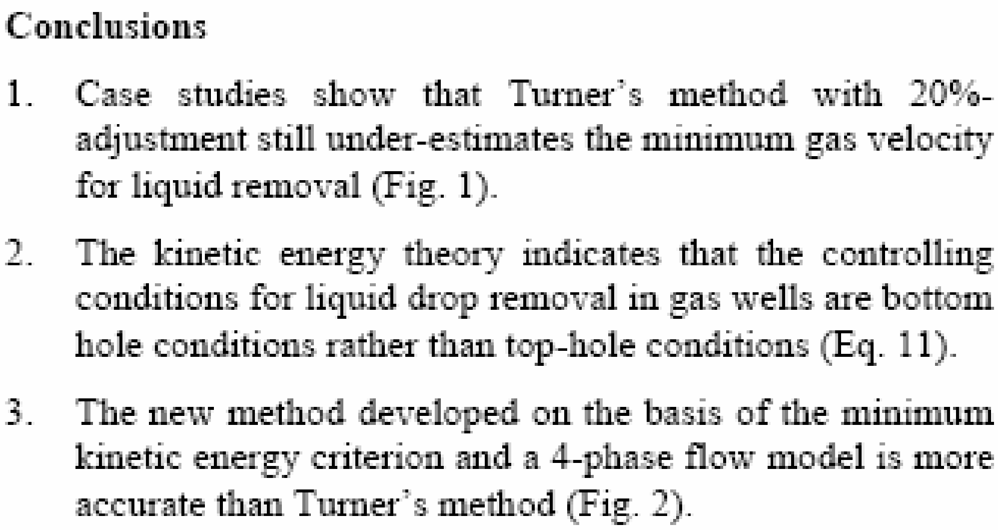
7. Duggan, J.O.: "Estimating Flow Rates Required to Keep Gas Wells Unloaded," *J. Pet. Tech.* (December 1961) 1173-1176.
8. Yamamoto, H. and Christiansen, R.L.: "Enhancing Liquid Lift from Low Pressure Gas Reservoirs," paper SPE 55625 prepared for presentation at the 1999 SPE Rocky Mountain Regional Meeting, Gillette, WY, May 15-18.
9. Bizanti, M.S. and Moonesan, A.: "How to Determine Minimum Flowrate for Liquids Removal," *World Oil*, (Sept. 1989) 71-73.
10. Ilobi, M.I. and Ikoku, C.U.: "Minimum Gas Flow Rate for Continuous Liquid Removal in Gas Wells," paper SPE 10170 presented at the 1981 SPE of AIME Annual Fall Technical Conference and Exhibition, San Antonio, TX, Oct. 5-7.
11. Guo, B., Ghalambor, A., Xu, C., " A Systemic Approach to Predicting Liquid Loading in Gas Wells", SPE 94081, Presented at the 2005 SPE Production and Operations Symposium, OK City, USA, 17-19, April, 2005.

Critical vs BWPD



Conclusions

1. Case studies show that Turner's method with 20%-adjustment still under-estimates the minimum gas velocity for liquid removal (Fig. 1).
2. The kinetic energy theory indicates that the controlling conditions for liquid drop removal in gas wells are bottom hole conditions rather than top-hole conditions (Eq. 11).
3. The new method developed on the basis of the minimum kinetic energy criterion and a 4-phase flow model is more accurate than Turner's method (Fig. 2).

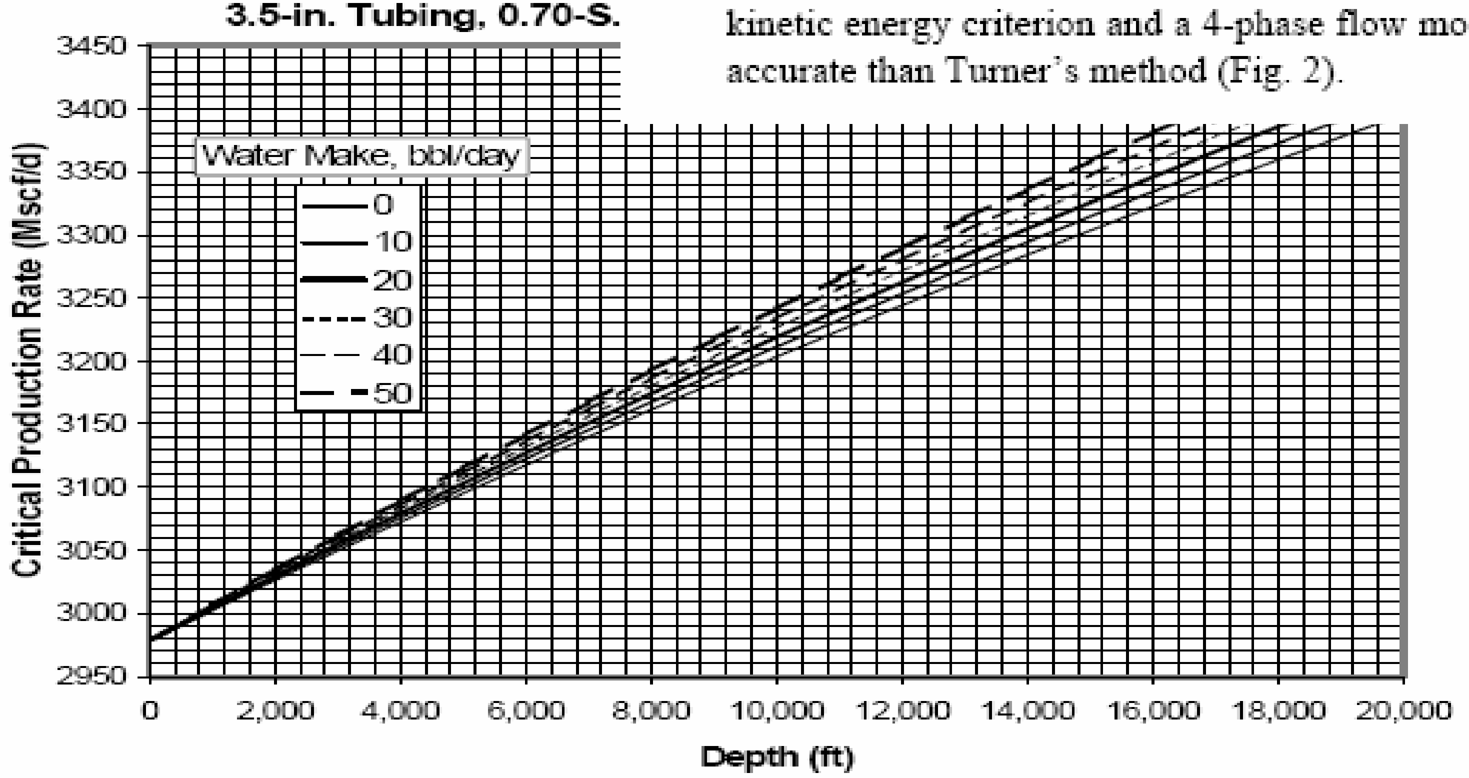


Fig. 3 – The critical gas production rates for water removal in a 3.5-inch tubing at wellhead pressure 900 psia.

Critical Rate: Summary

- Turner, Coleman and other models do not agree
- Most except Guo et al. are in dependent of liquid rate
- It is theoretically better to use at pressure downhole but seldom done
- Most critical models are fairly simplistic models
- Must be considered approximate but widely used with fair success
- New model with critical as fn of bwpd seems logical but untested by industry as far as is known

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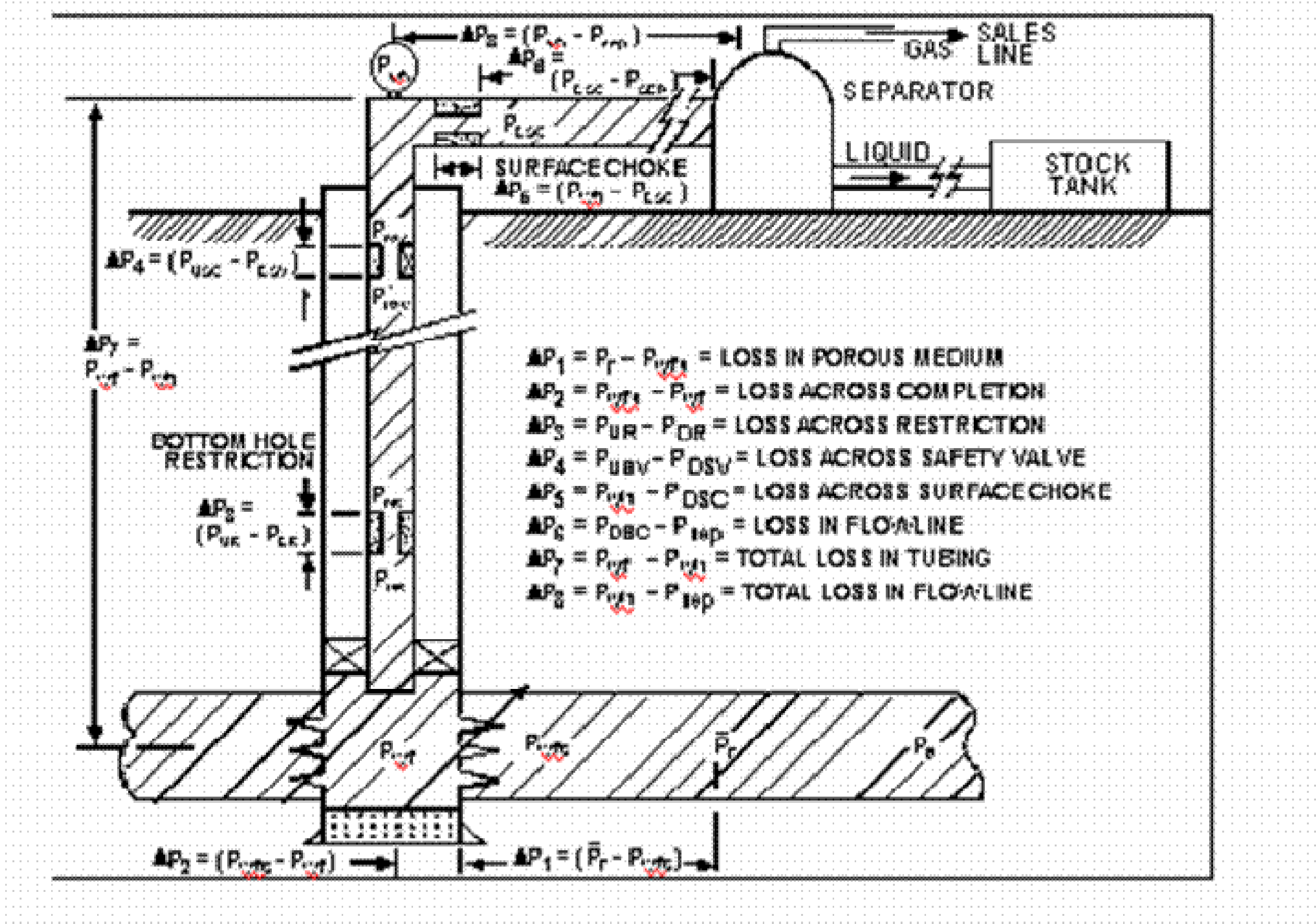
Nodal Analysis

Nodal Analysis ™ :

A Model of the Well



$\Delta P_1 = P_r - P_{wfs}$ = LOSS IN POROUS MEDIUM

$\Delta P_2 = P_{wfs} - P_{wf}$ = LOSS ACROSS COMPLETION

$\Delta P_3 = P_{UR} - P_{DR}$ = LOSS ACROSS RESTRICTION

$\Delta P_4 = P_{USV} - P_{DSV}$ = LOSS ACROSS SAFETY VALVE

$\Delta P_5 = P_{wh} - P_{DSC}$ = LOSS ACROSS SURFACE CHOKE

$\Delta P_6 = P_{DSC} - P_{sep}$ = LOSS IN FLOWLINE

$\Delta P_7 = P_{wf} - P_{wh}$ = TOTAL LOSS IN TUBING

$\Delta P_8 = P_{wh} - P_{sep}$ = TOTAL LOSS IN FLOWLINE

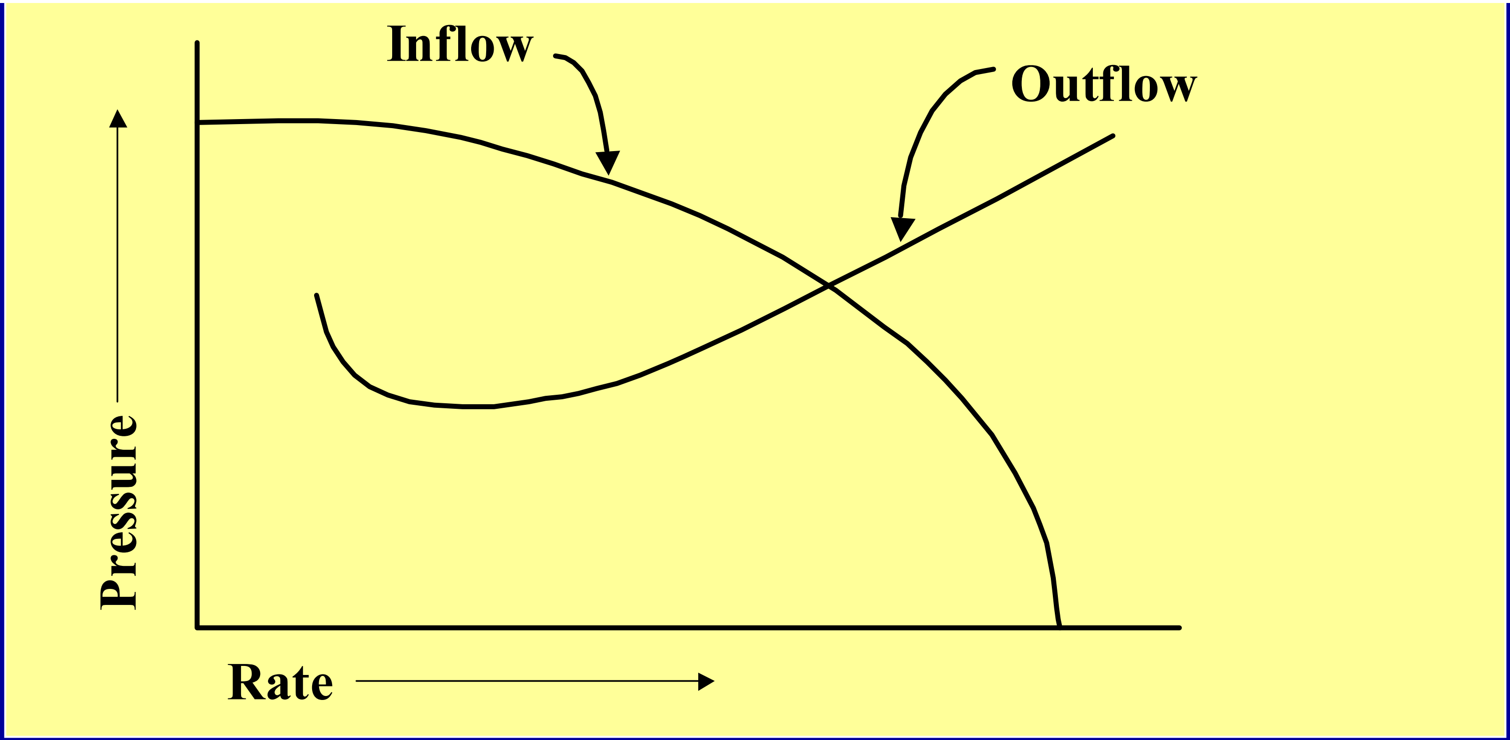
Nodal Analysis ™ (SLB)

Inflow to the node

PR – ΔP (upstream components press drop's) = Pnode

Outflow from the node

Psep + Δ P (downstream components press drop's) = Pnode

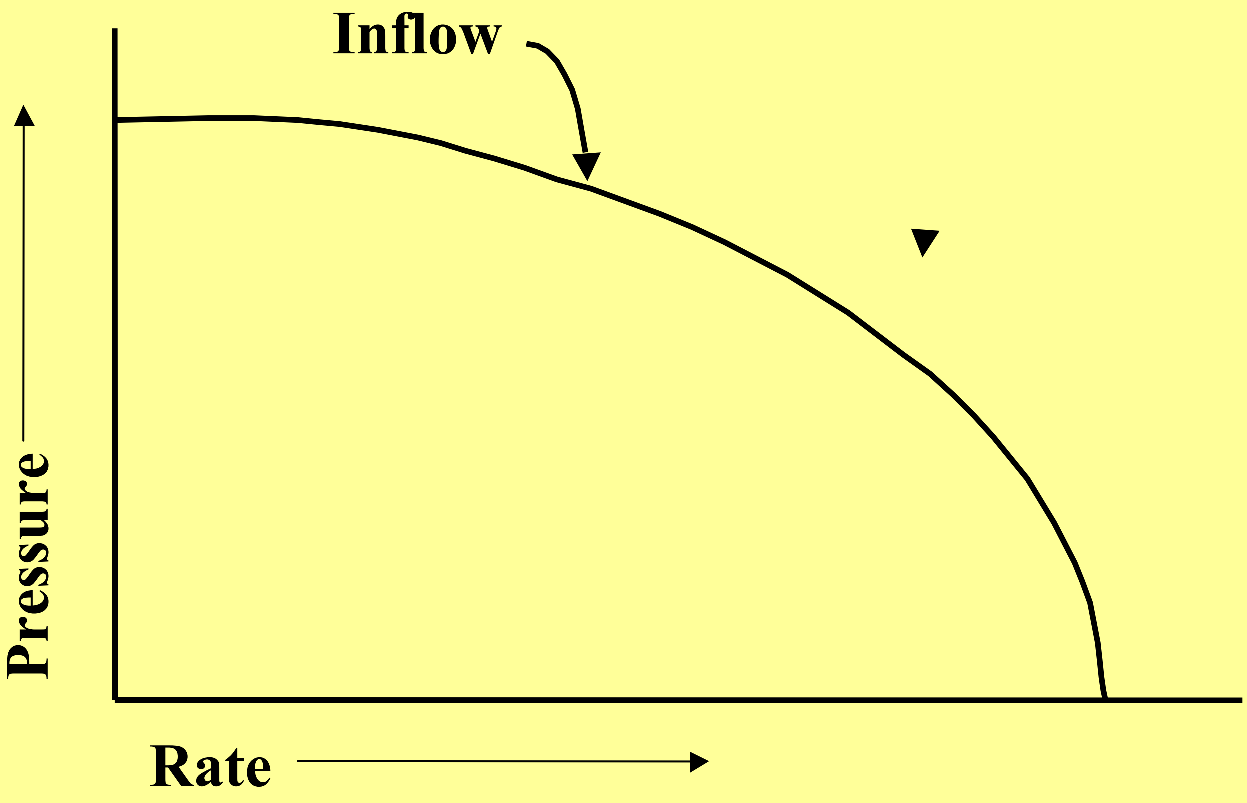


Inflow Curves

Inflow or Reservoir Curve

Reservoir Inflow curve often represented by:

$Q = C\ (\ Pr^2 – Pwf^2)^n$ …. (back pressure equation)



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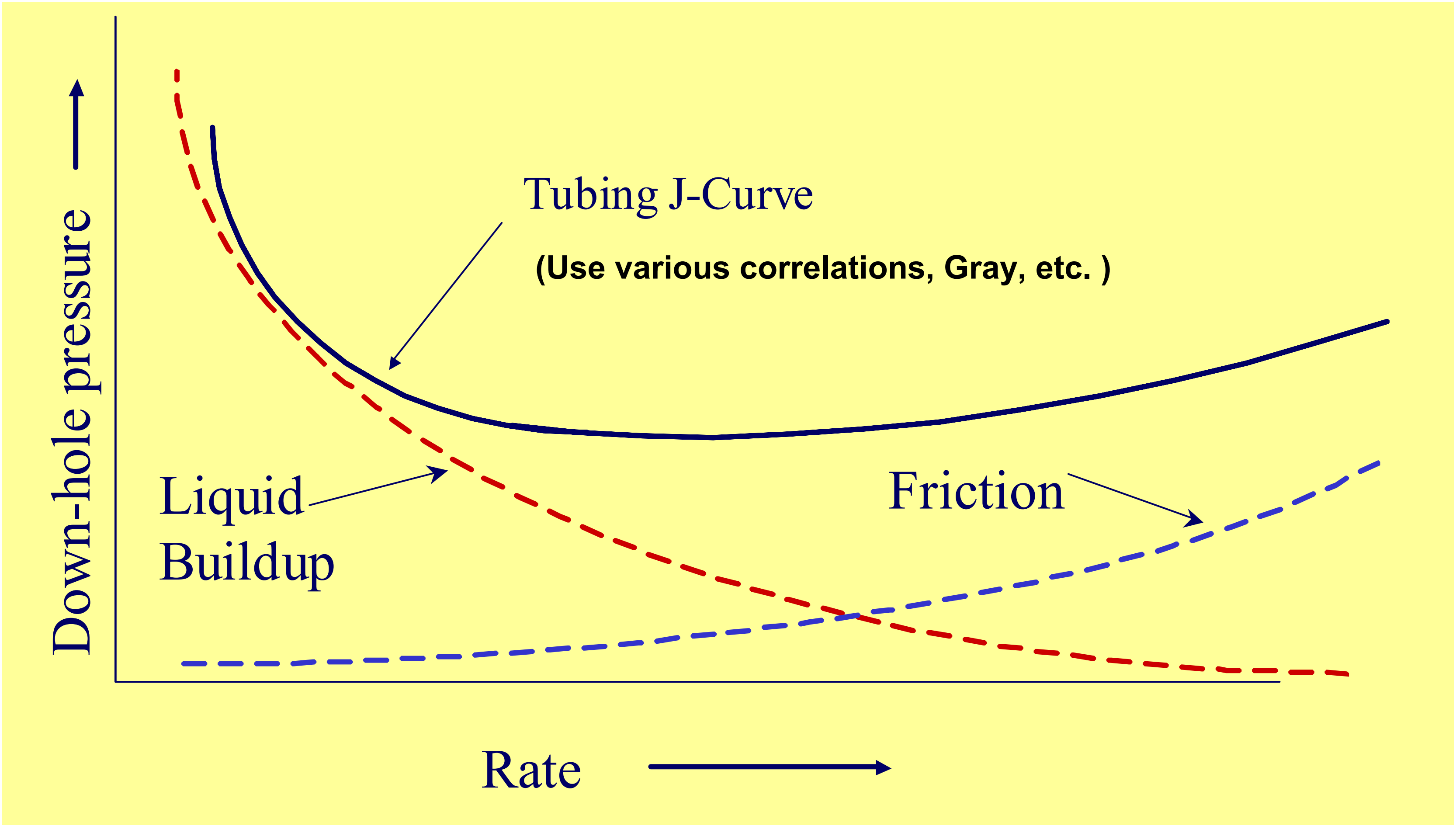
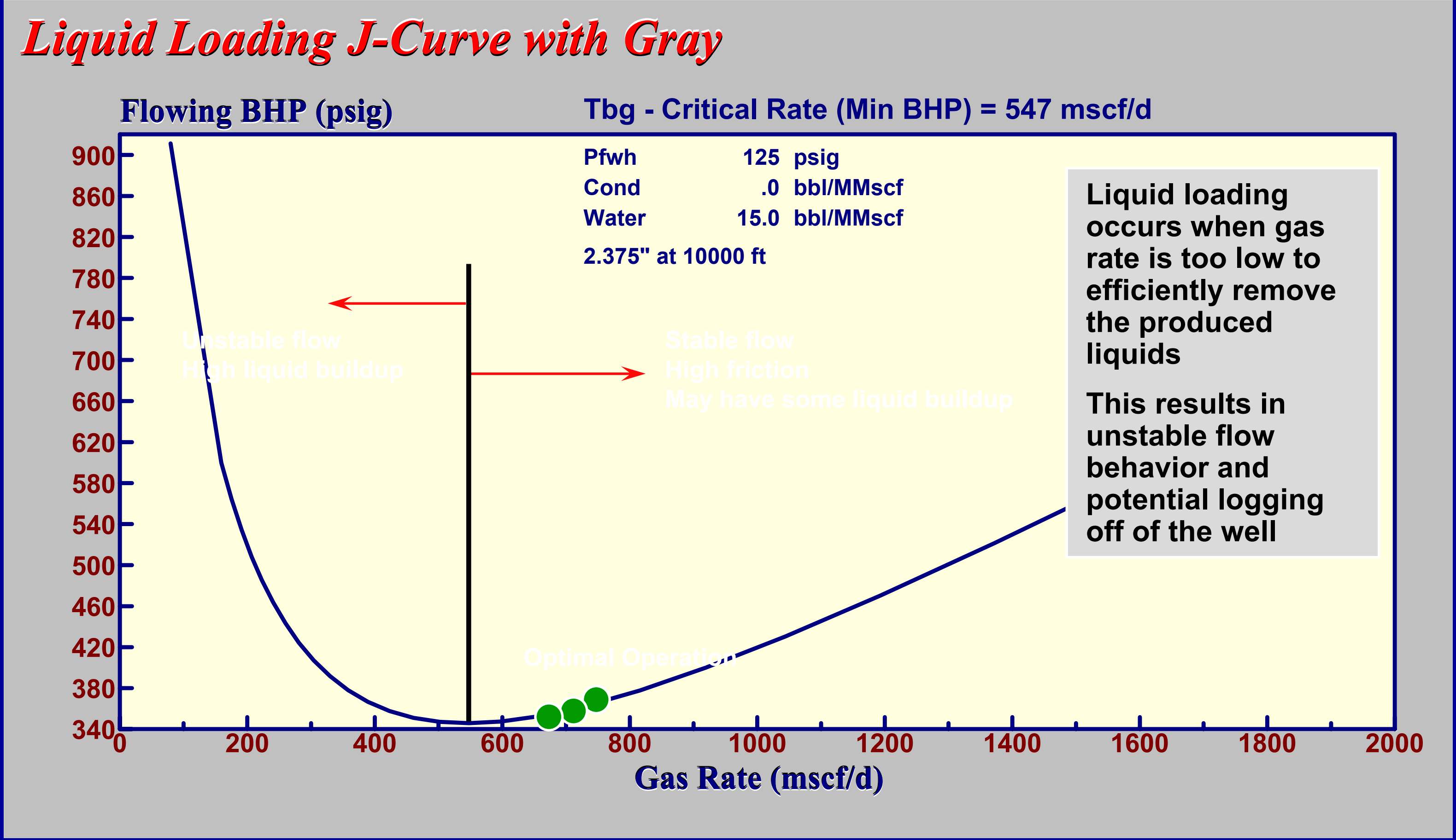
Outflow Curves

Nodal Analysis ™ (SLB)

At low rates, liquid builds up in the tubing and requires more pressure to flow



Liquid Loading
J-Curve with Tubing to Perfs



Liquid loading occurs when gas rate is too low to efficiently remove the produced liquids

This results in unstable flow behavior and potential logging off of the well

Flowpoint: Greene, SWPSC

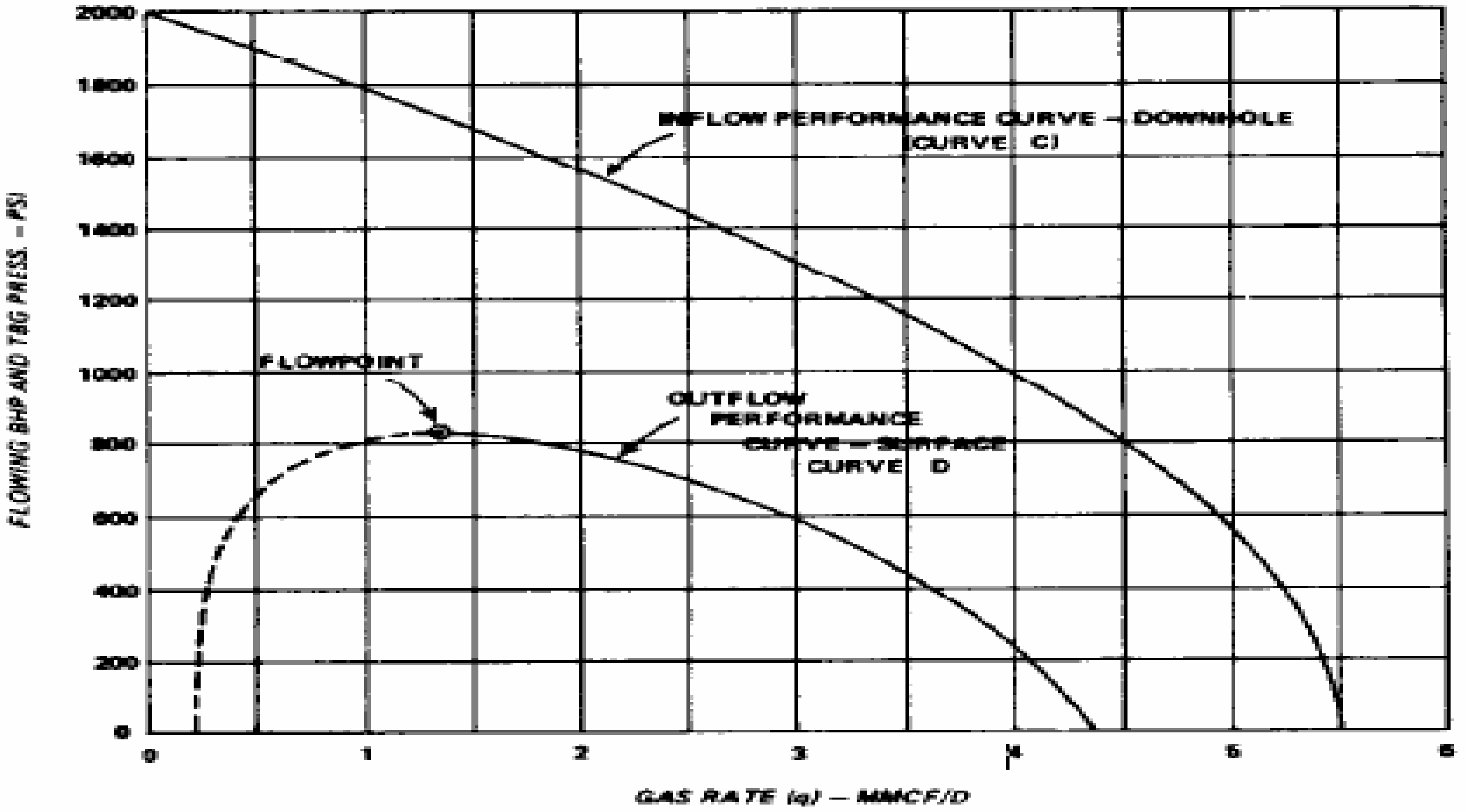
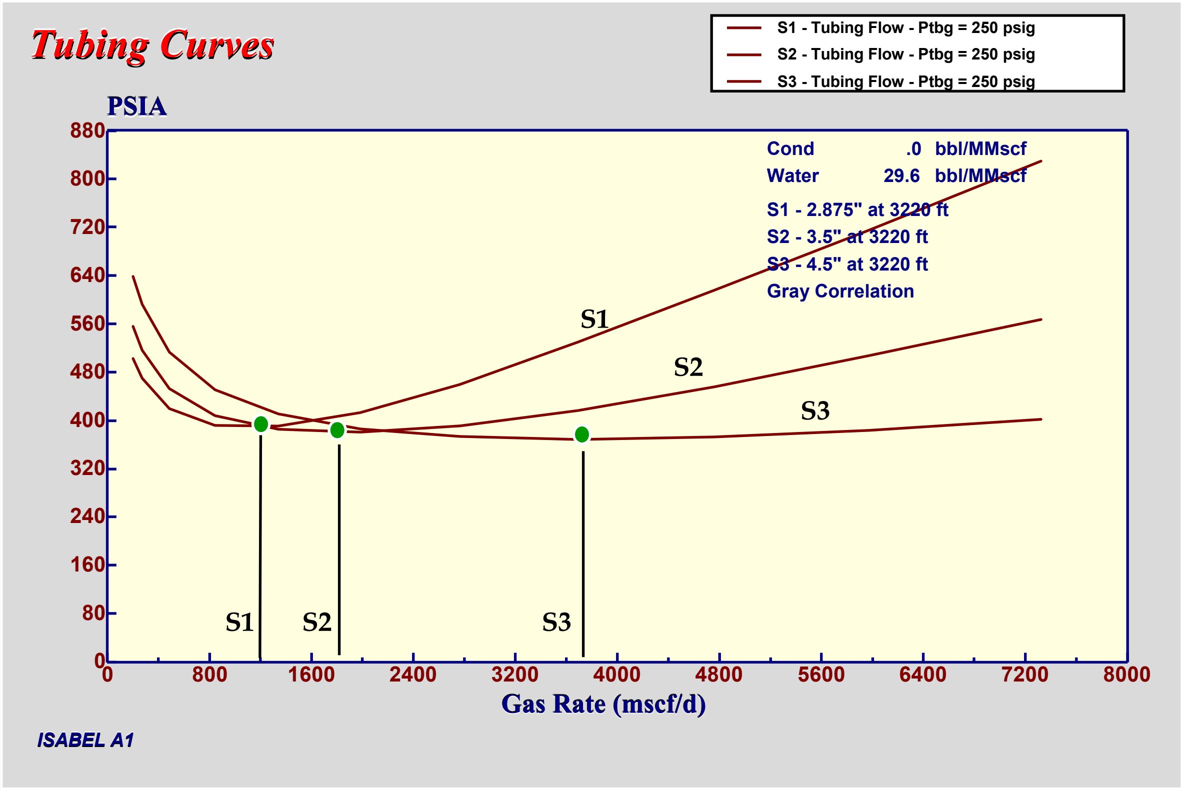


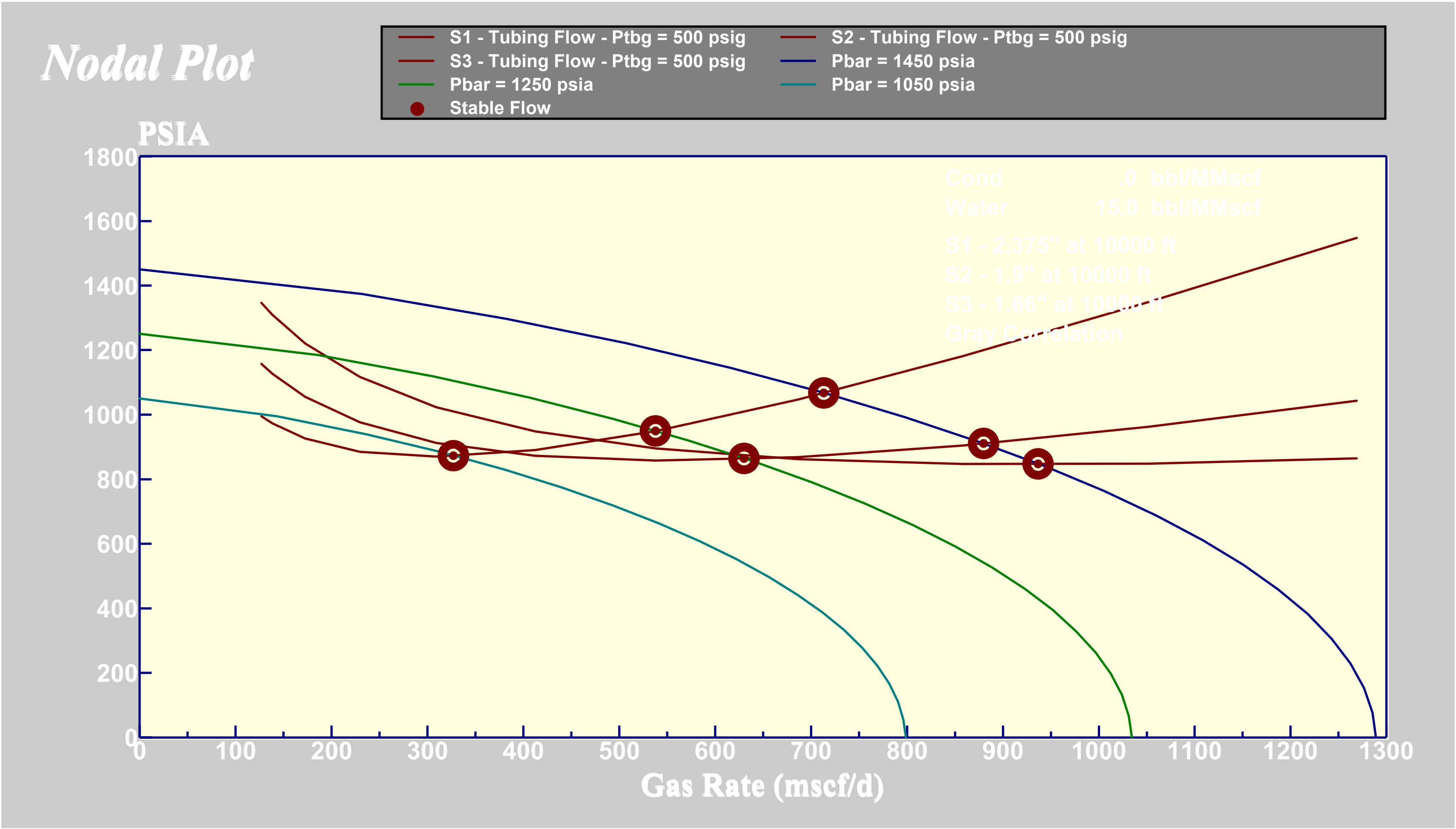
FIGURE 4—OUTFLOW PERFORMANCE CURVES

Liquid Loading

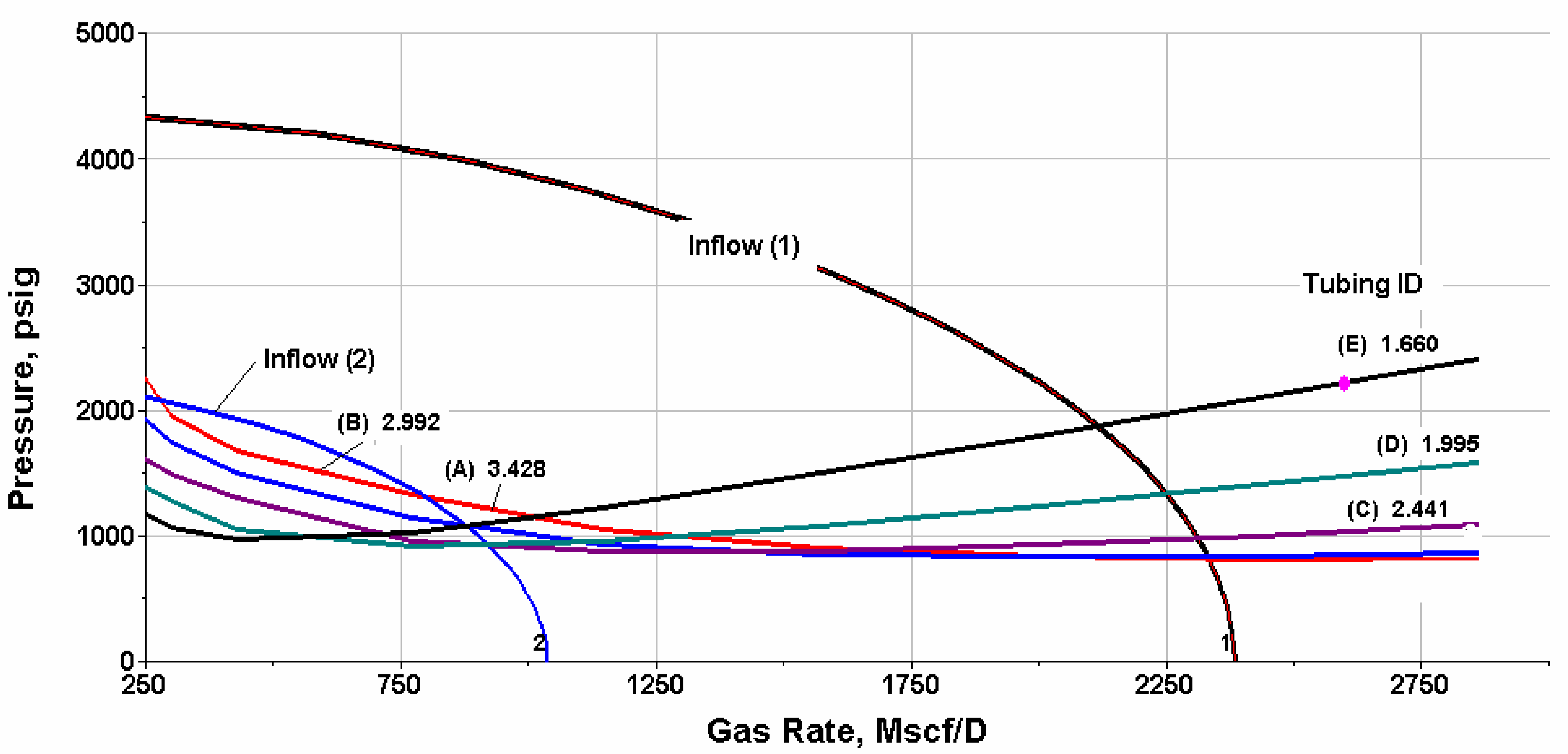
- Liquid loading occurs when gas rate is too low to efficiently remove the produced liquids
- This results in unstable flow behavior and potential logging off of the well



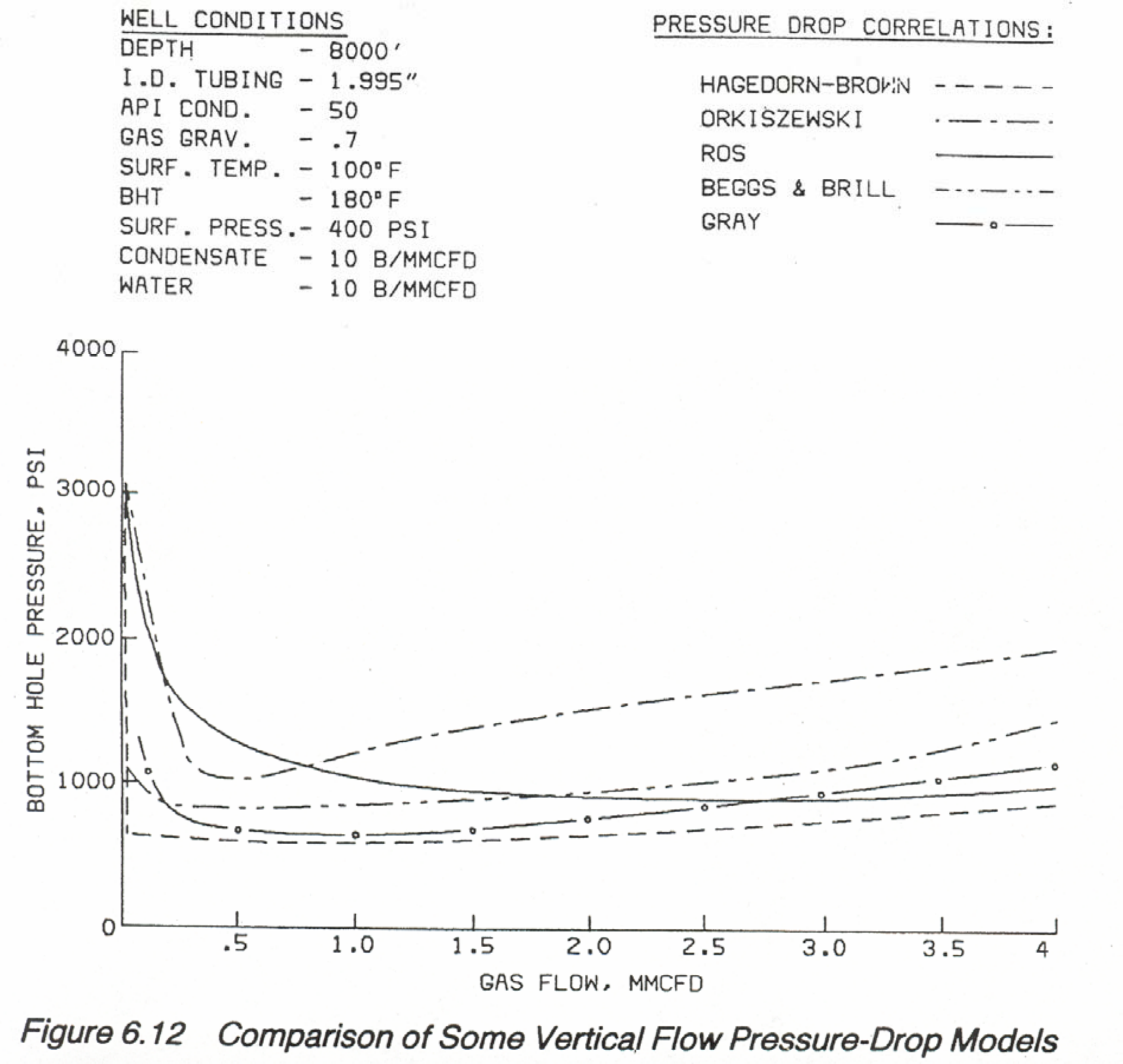
Liquid Loading
Effect of Tubing String



Nodal Analysis : Effects such as Size of the Tubing Diameter vs. Flow Rate can be studied



Nodal "Turn-Up" Point is <u>BIGGEST ERROR</u> in Multiphase Flow Predictions

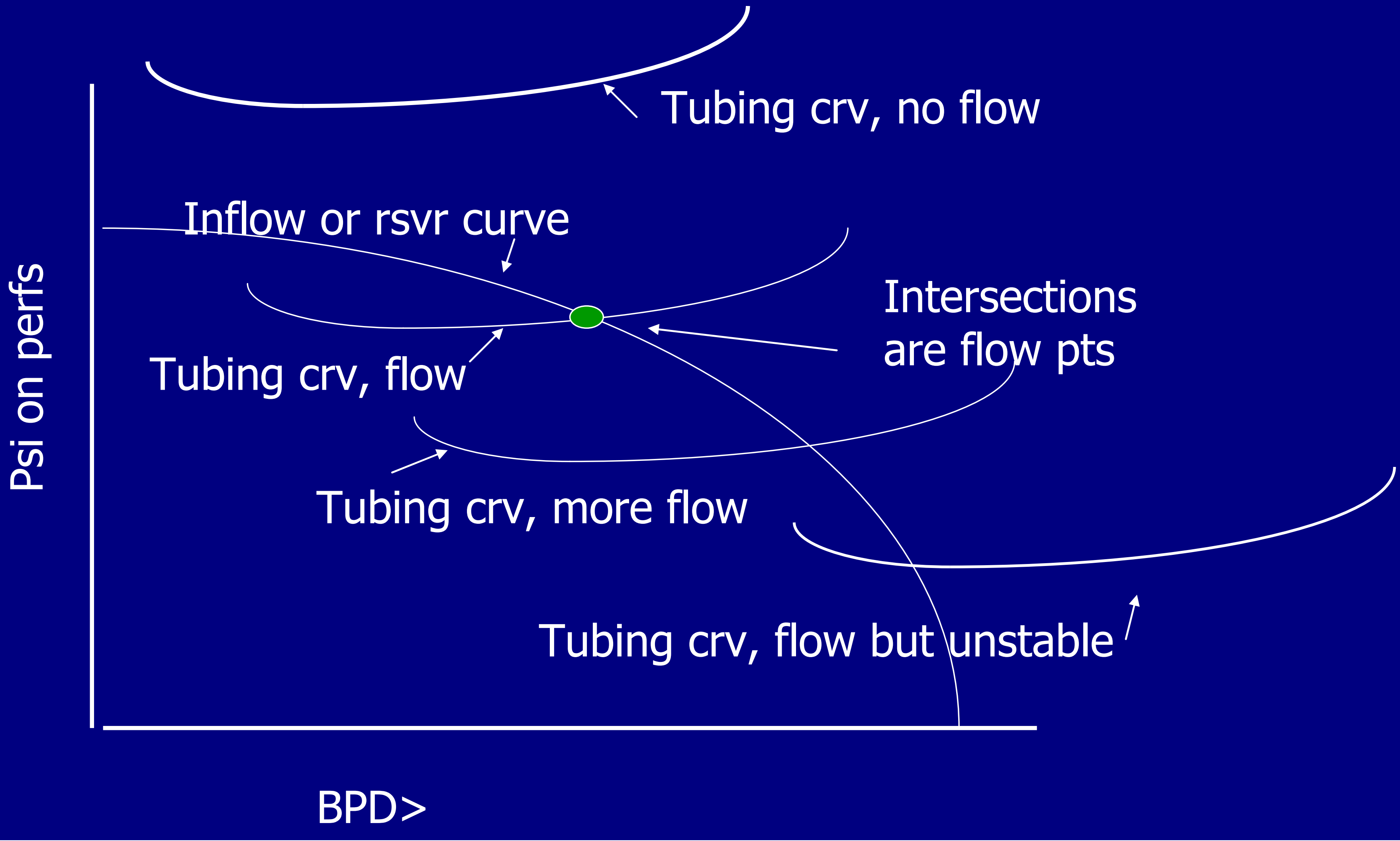


WELL CONDITIONS
DEPTH - 8000'
I.D. TUBING - 1.995"
API COND. - 50
GAS GRAV. - .7
SURF. TEMP. - 100°F
BHT - 180°F
SURF. PRESS.- 400 PSI
CONDENSATE - 10 B/MMCFD
WATER - 10 B/MMCFD

Figure 6.12 Comparison of Some Vertical Flow Pressure-Drop Models

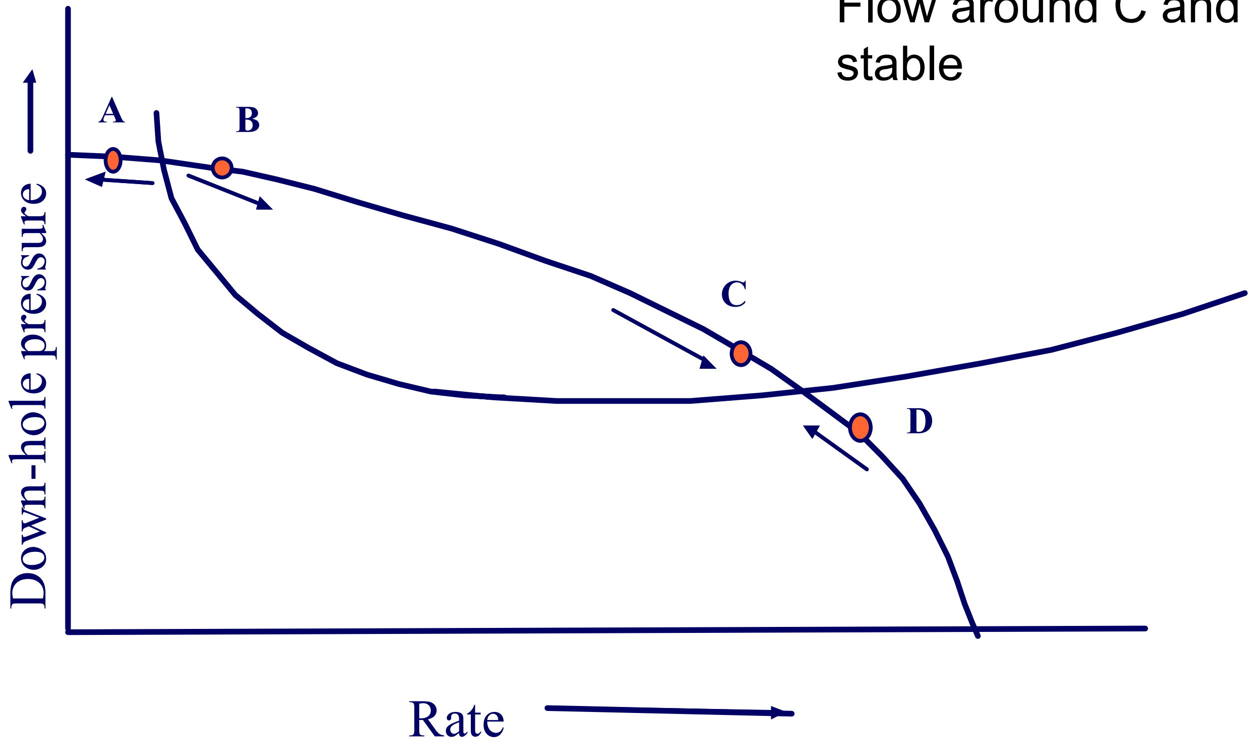
Nodal Stability

Nodal Analysis Well Situations



Nodal Analysis : Stability

Stability



Flow around A & B is unstable

Flow around C and D is stable

What About Flow Below the Critical???

- Exxon said on average with their data, production was 40% less
- Sutton, et al., Marathon, SPE 80887 modeled flow with gas bubbling through static liquid column.

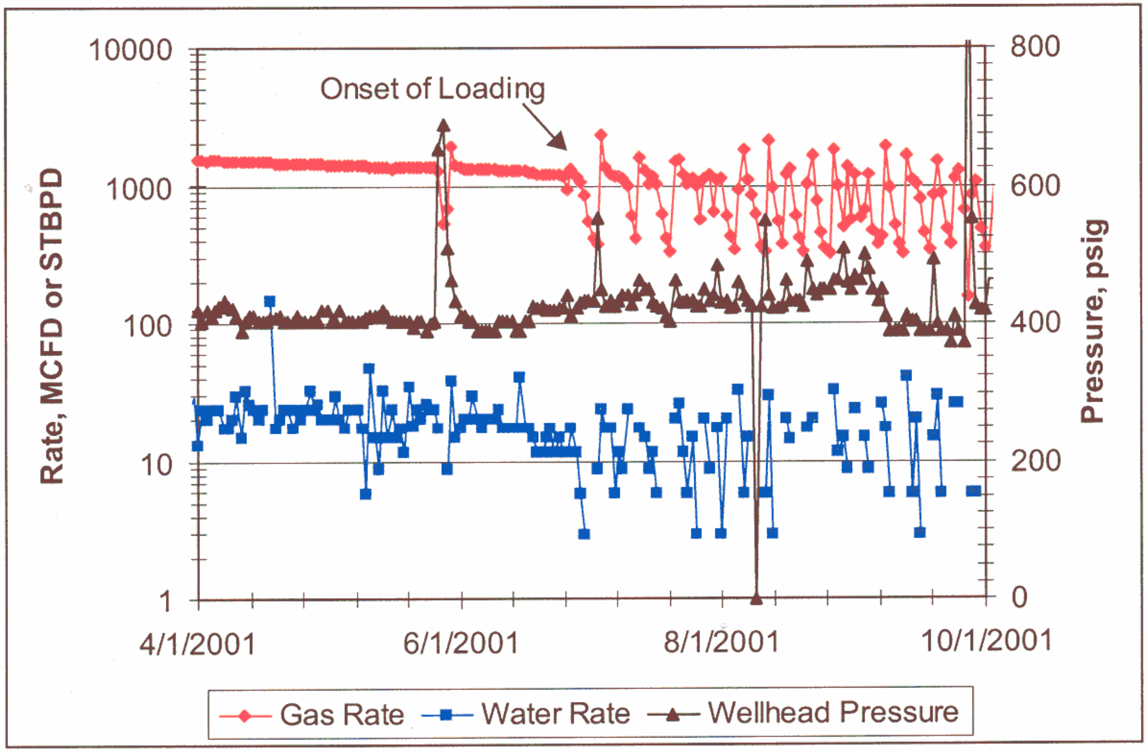


Fig. 4 – Example of Well Performance with Liquid Loading

Model Gas Well

Example Gas Well

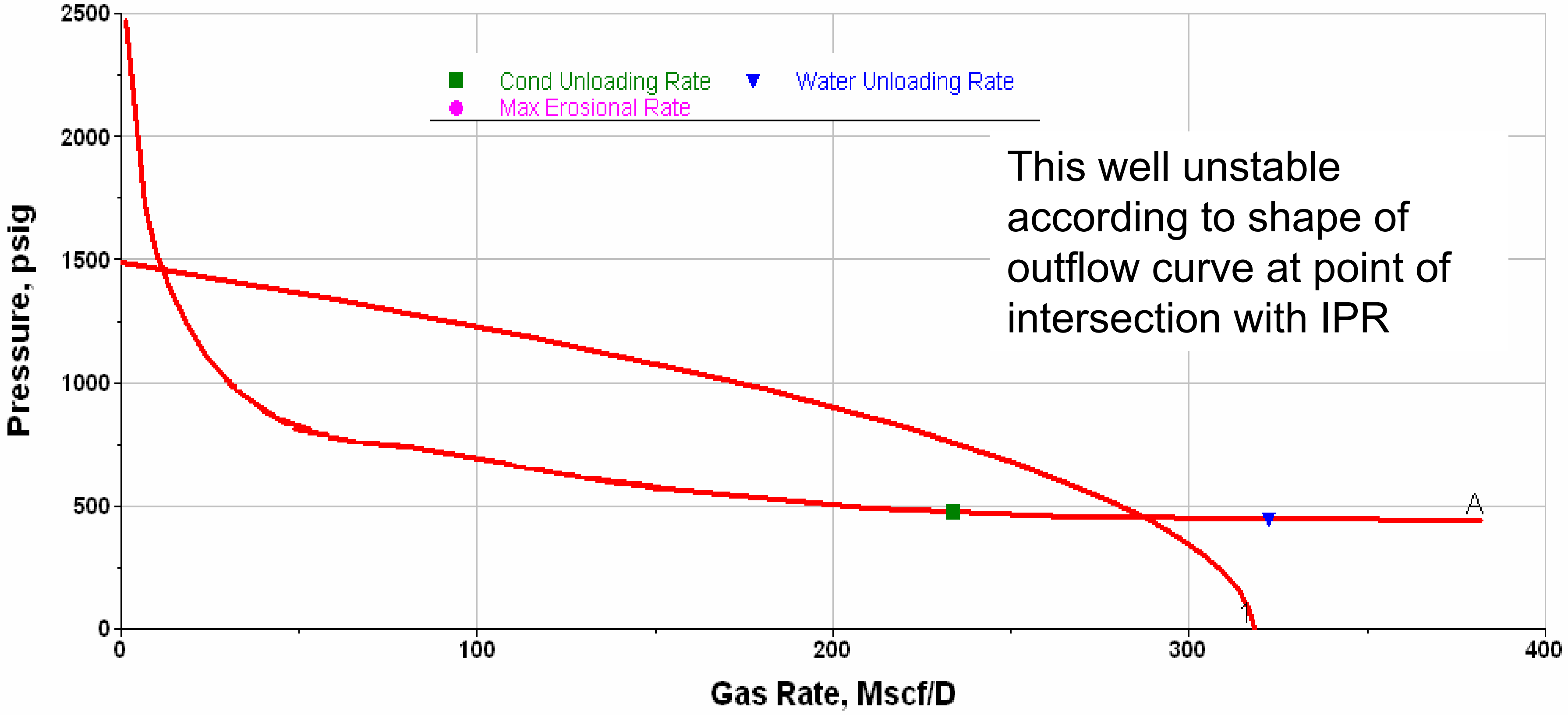
- Data:
- Reservoir:
- C = .0001414 Mscf/D
- n = 1.0
- Pr =1500 psi
- Tubing: 2 3/8's to 10,000'
- Liquids: 50 bbl/MMscf

SNAP: Ryder Scott

- Pressures/Temps/Fluid Properties
- Pwh: 100 psi
- Twh: 100 F
- BHT: 200 F
- GG: .7
- WG: 1.03
- WOR: 1.

Example Output

Well Unstable and Also Flowing Below Critical for Water



This well unstable according to shape of outflow curve at point of intersection with IPR

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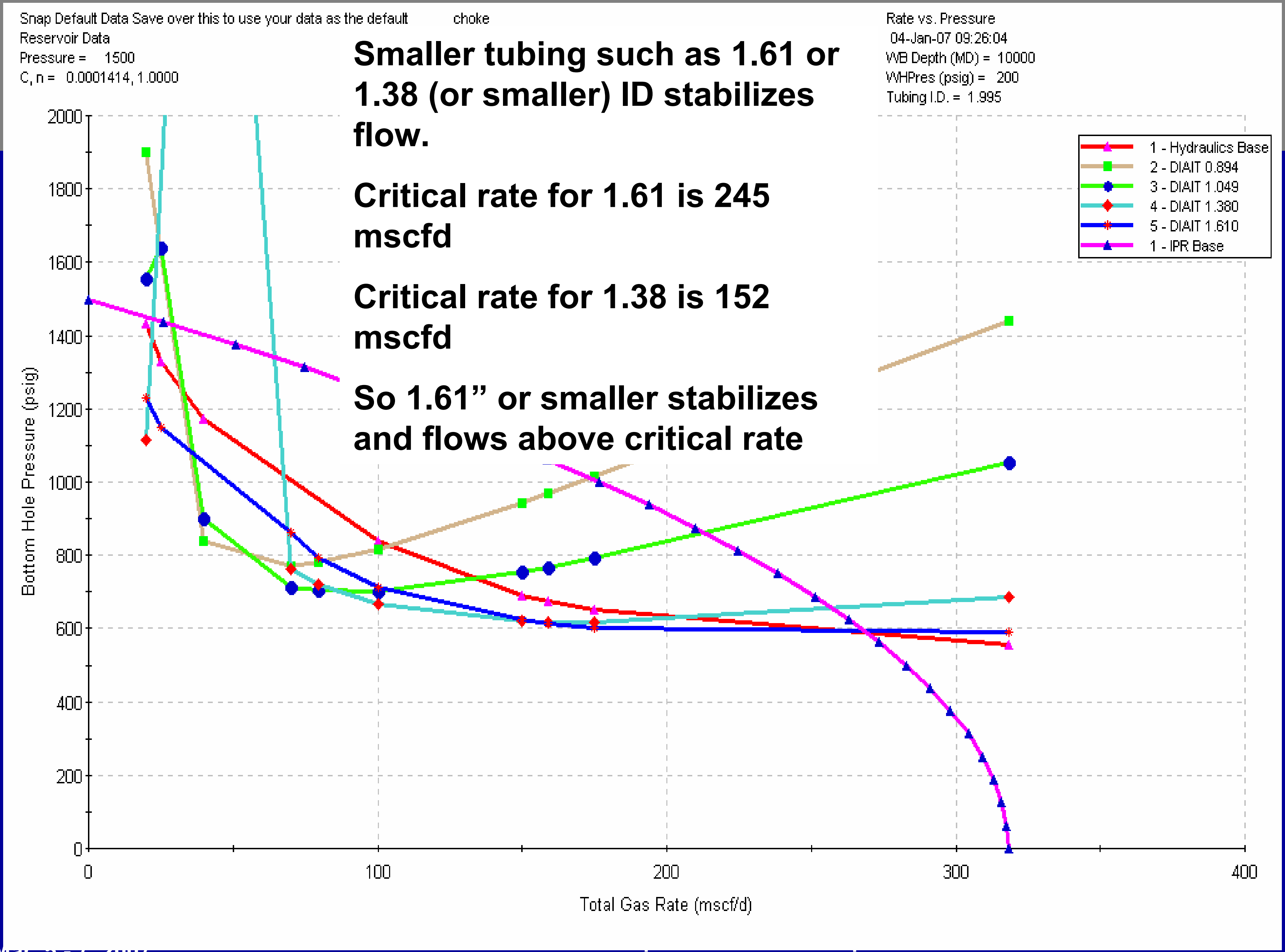
Effects of Tubing Size



Snap Default Data Save over this to use your data as the default choke

Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:26:04
WB Depth (MD) = 10000
WHPres (psig) = 200
Tubing I.D. = 1.995

Smaller tubing such as 1.61 or 1.38 (or smaller) ID stabilizes flow.

Critical rate for 1.61 is 245 mscfd

Critical rate for 1.38 is 152 mscfd

So 1.61” or smaller stabilizes and flows above critical rate

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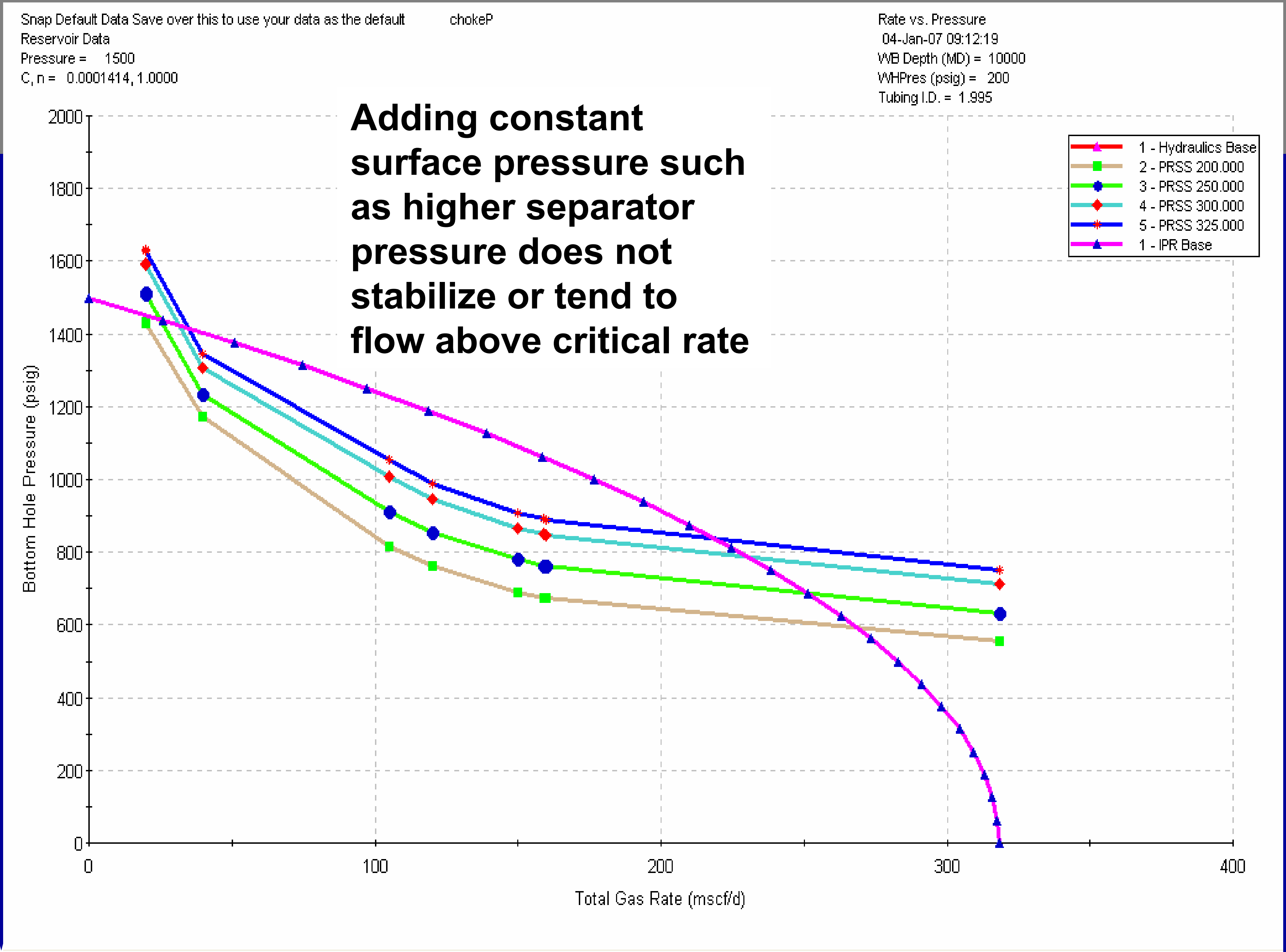
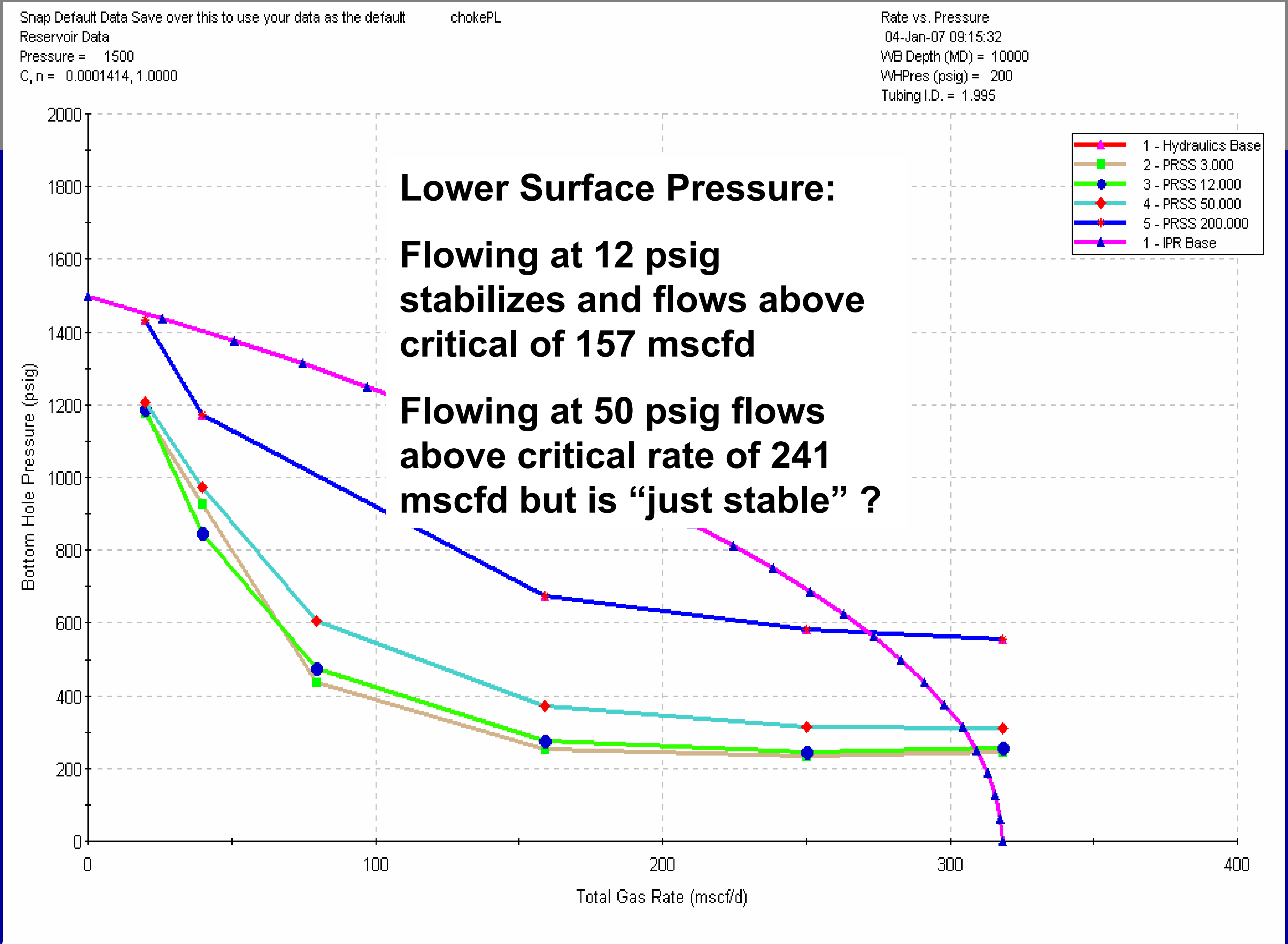
Effects of Surface Pressure


Snap Default Data Save over this to use your data as the default chokeP
Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:12:19
WB Depth (MD) = 10000
WHPres (psig) = 200
Tubing I.D. = 1.995

Adding constant surface pressure such as higher separator pressure does not stabilize or tend to flow above critical rate



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Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:15:32
WB Depth (MD) = 10000
WHPres (psig) = 200
Tubing I.D. = 1.995

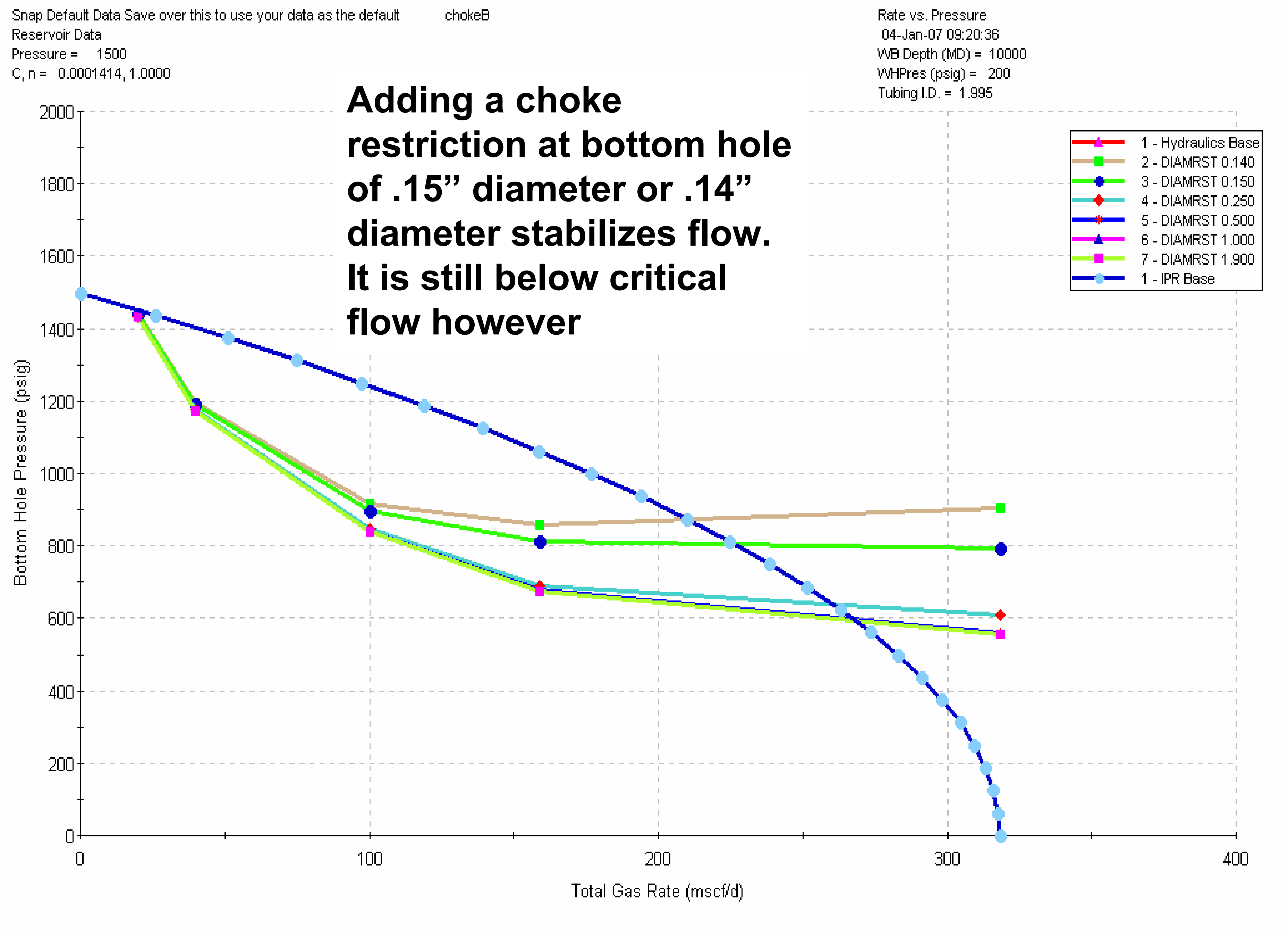
Lower Surface Pressure:

Flowing at 12 psig stabilizes and flows above critical of 157 mscfd

Flowing at 50 psig flows above critical rate of 241 mscfd but is “just stable” ?

Effects of Restrictions at Bottom of Tubing

Adding a choke restriction at bottom hole of .15” diameter or .14” diameter stabilizes flow. It is still below critical flow however



Snap Default Data Save over this to use your data as the default chokeB
Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:20:36
WB Depth (MD) = 10000
WHPres (psig) = 200
Tubing I.D. = 1.995

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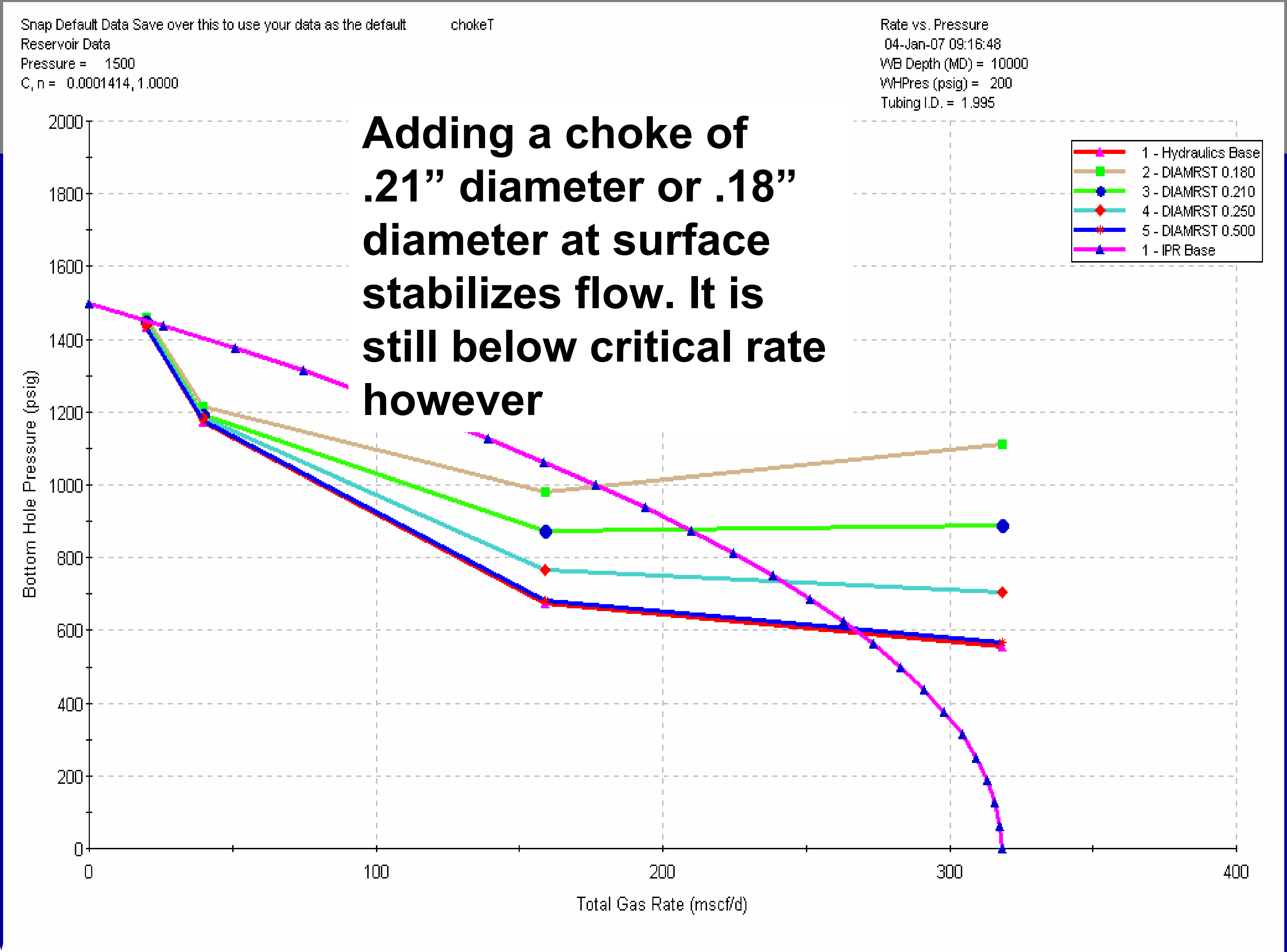
Effects of Restrictions at Surface



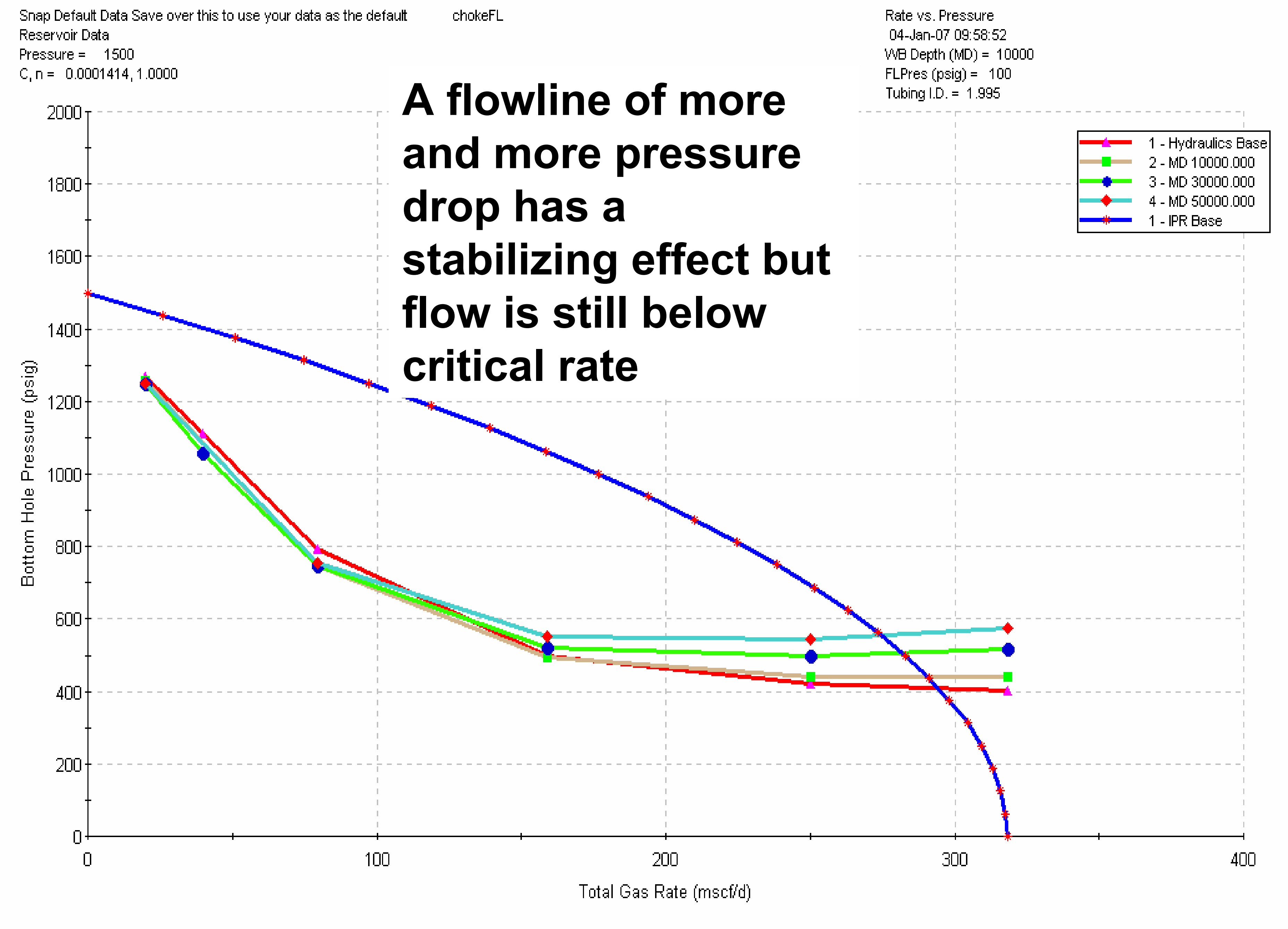
Snap Default Data Save over this to use your data as the default chokeT
Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:16:48
WB Depth (MD) = 10000
WHPres (psig) = 200
Tubing I.D. = 1.995

Adding a choke of .21” diameter or .18” diameter at surface stabilizes flow. It is still below critical rate however

Effects of Flowline

A flowline of more and more pressure drop has a stabilizing effect but flow is still below critical rate



Snap Default Data Save over this to use your data as the default chokeFL
Reservoir Data
Pressure = 1500
C, n = 0.0001414, 1.0000

Rate vs. Pressure
04-Jan-07 09:58:52
WB Depth (MD) = 10000
FLPres (psig) = 100
Tubing I.D. = 1.995

Summary & Conclusions

Summary & Conclusions

- Smaller tubing has stabilizing effect but if too small will add too much friction (well known)
- Adding constant pressure to the surface of the well reduces rate and does not stabilize the well or tend to flow below critical
- Adding lower constant pressure to the surface of the well stabilizes the well and tends to flow above critical rate (compression)
- Adding a rate dependent pressure drop (choke) to bottom or top of well has stabilizing effect but flow remains below critical rate if below critical to begin with

Summary & Conclusions Continued

- The effects of a flowline (rate dependent pressure drop) has a stabilizing effect on the flow but flow continues below critical if below to start with as FL pressure drop is added.
- Never add rate dependent pressure drop (choke) to a well that is flowing above critical rate.. It will only reduce flowrate
- Adding too much of a rate dependent pressure drop (choke) will/can reduce flowrate to zero

Summary & Conclusions Continued

- In general never add a rate dependent pressure drop to plunger lift, or pumping wells or gaslift wells. There are some exceptions where back pressure may help beam handle gas better and choking gaslift well can sometimes reduce heading and cycling.

Questions Remaining

- Since Nodal Analysis shows a stabilizing effect on a loaded gas well only, (but still flows below critical rate), does this explain the anecdotal cases where adding chokes to wells in the field gets them to flow continuously where they would not before?
- Cases are reported where wells that require stop clocking will flow continuously if a choke is added to the surface. It may serve as intermediate solution to loading before AL is needed.
- Is critical rate alone good enough to evaluate loading wells or is Nodal Analysis also to evaluate stability?

Problems

- Multiphase correlations have poor agreement to evaluate stability in loaded/unloaded gas wells
- Critical velocity correlations also disagree and have problems previously discussed

Better?

Numerical and Analytical Modeling of the Gas-Well Liquid-Loading Process

Niek Dousi, Delft U. of Technology, **C.A.M. Veeken,** Shell E&P Europe, and
Peter K. Currie, SPE, Delft U. of Technology

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Possible Uses of Analysis

- If a well is loaded and it must be intermitted to continue production, consider using a choke to get the well to flow continuously once again. The cost is low to try this.
- DO NOT add chokes across the field indiscriminately or you will have problems.
- Thanks to Mohan Kelkar, Tulsa University, for pointing out the stabilizing effects of adding chokes to loaded gas wells. At least stabilizing as far as Nodal Analysis predictions are concerned. He also has reported success stories with this technique.

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